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Exploring impacts of vegetated buffer strips on nitrogen cycling using a spatially explicit hydro-biogeochemical modeling approach

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A B S T R A C T

Agriculture has been recognized as a major anthropogenic source of surplus loads of nitrogen in the environment. Losses of nitrate via subsurface pathways are severely threatening groundwater and surface waters. This study explored the capability of a coupled hydro-biogeochemical spatially explicit model, simulating nitrogen cycling in agricultural soils and the associated fate of excess nitrate subjected to vertical and lateral displacement towards water bodies. Different vegetated buffer strips (VBS) were tested for their nitrate retention capability and impacts on N_2O and N_2 emissions. The effectiveness of a VBS to remove nitrate by denitrification strongly depends on soil characteristics and hydrological flow paths. Simulated N_2 emissions from VBS with high soil moisture were up to twenty-fold compared to VBS where groundwater levels were low. Simulated streamwater nitrate concentrations without VBS were 3.7 mg NO_3^- l^{-1} and showed a decrease to 0.1 mg NO_3^- l^{-1} for a 20 m VBS.

Software and availability

Name of software CMF.
Developers ILR; contact: Philipp Kraft.
E-mail philipp.kraft@umwelt.uni-giessen.de.
Address ILR, Heinrich-Buff-Ring 26, 35392 Giessen, Germany.
Availability Open source (GNU GPLv3 license) via website http://fb09-pasig.umwelt.uni-giessen.de/cmf.
Program language C/C++.
Program size 4 MB.
Name of software LandscapeDNDC.
Developers IMK-IFU, KIT; contact Ralf Kiese.
E-mail ralf.kiese@kit.edu.
Address IMK-IFU, KIT, Kreuzeckbahnstrasse 19, 82467 Garmisch-Partenkirchen, Germany.
Availability Freeware, upon request via website http://ldndc.imk-ifu.kit.edu.
Program language C/C++.
Program size 20 MB.

1. Introduction

Nitrate (NO_3^-) is a serious threat to surface waters and groundwater causing eutrophication. As such, it severely puts the quality of drinking water at risk (Lavelle et al., 2005; Kiese et al., 2011). According to Erisman et al. (2013) high nitrate loads were observed during 2000 and 2003 at roughly half of European groundwater and surface water monitoring stations. For example, in French Brittany approximately 80% of surface waters are estimated to exceed nitrate levels of 50 mg l^{-1} set as the maximum value for drinking water by the European Commission (Molénat and Gascuel-Odoux, 2002).

Efforts to establish good water quality throughout the European

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Union (EU) are regulated by the Urban Waste Water Treatment Directive (UWWTD) (Directive 91/271/EEC) and the Nitrates Directive (ND) (Directive 91/676/EEC) since 1991 indicating that the significance for this matter has been recognized. Bouraoui and Grizzetti (2014) report that the contributions from point sources (e.g., livestock confinements) to water pollution has been significantly reduced after implementation of the UWWTD. In contrast, non-point (diffuse) sources of nitrate (e.g., use of organic and inorganic fertilizers) whose abatement is also addressed by the ND are still a major concern (Bouraoui and Grizzetti, 2011; Withers et al., 2014). In fact, after substantially reducing point source pollution the impact from diffuse sources became more apparent (Heathwaite et al., 2005; Brown Gaddis et al., 2007). In a study to quantify the nitrogen (N) inputs to European coastal areas, Grizzetti et al. (2012) found large variations between monitoring sites attributed to the high variability of the factors driving nitrogen losses, in particular NO_3^- discharge, to water bodies. Such factors include soil and hydrologic properties, slope, climate, vegetation and anthropogenic activities which highlight that deriving commonly applicable mitigation measures is likely to fail (Howden et al., 2011; Kamprath et al., 2000). Instead, to cover this complexity appropriate mitigation options need to consider site-specific characteristics (Gömann et al., 2005) to counteract this problem which is common in agriculture in all parts of the world.

One of the primary sources of diffuse pollution is agriculture (Cherry et al., 2008; Withers et al., 2014), which was estimated to contribute more than 50% of total nitrogen inputs to European seas in the year 2005 (Grizzetti et al., 2012). In the coming decades, agricultural production will need to sustain a globally growing population while available land suitable for agricultural use is limited (Bloom et al., 2011; Parry and Hawkesford, 2010; Godfray, 2014). For this reason, intensification of agriculture, which is mostly associated with the growing use of nitrogen fertilizers (Galloway et al., 2004; McKenzie and Williams, 2015), is likely to continue. Excessive use of organic and inorganic fertilizers as well as improper timings of their application, e.g., at times without or with only limited plant growth, are among the prevalent agricultural practices responsible for elevated nitrate loads in nearby water bodies (e.g., Cherry et al., 2008). Nitrate may also be transformed by microbial metabolism in the soil (denitrification) causing gaseous losses of nitrogen, e.g., nitrous oxide (N_2O), nitric oxide (NO) and dinitrogen (N_2) (Butterbach-Bahl et al., 2013). Because N_2O is a very potent greenhouse gas, trading NO_3^- for N_2O is an example of pollution swapping (Stevens and Quinton, 2009).

Consequently, developing and evaluating measures for sustainable agriculture that do not compromise the quality of ecosystem services is crucial. However, due to the complex interaction of the water and nitrogen cycling and their dependence on site-specific properties (e.g., soil type, management and climate) a reliable assessment of the effectiveness of various mitigation options remains challenging (Stevens and Quinton, 2009; Mayer et al., 2007). In addition, there exists a considerable time-lag observed between changes in agricultural practices and their effects with respect to nitrogen emissions and nitrate discharge of up to decades (Grimvall et al., 2000; Fenton et al., 2011). Such temporal delays are attributed to time scales on which nutrient displacement processes in the soil operate and may hamper a correct interpretation of effects of mitigation options.

Recent advances in process-based eco-hydrological modeling (e.g., Pohlert et al., 2007; Panagopoulos et al., 2012) have made simulation models effective tools to overcome these problems and evaluate impacts of mitigation options on nitrogen losses for varying environmental conditions from catchment to continental scales. Recently, Kim et al. (2015) used a Monte-Carlo method applying the model LandscapeDNDC to estimate the potential of management options to reduce nitrate leaching from an intensely cultivated catchment in South Korea that is a source watershed for metropolitan residents. By altering the amount and timings of fertilizer applications, this study found fertilization regimes reducing NO_3^- leaching by up to 81% without impairing yields. On large scales, process-based models with semi-distributed hydrology components, e.g., INCA (Flynn et al., 2002), HYPE (Arheimer et al., 2015), SWAT (Laurent and Ruelland, 2011) have been used to assess changes in nitrate loads in ground- and surface waters induced by reduced fertilization, planting of catch crops or establishment of riparian buffer strips. These studies consider surface runoff, aquifer and river flow but put less emphasis on detailed subsurface water and nutrient fluxes in the unsaturated zone, where water driven biogeochemical processes have major impact on nitrogen transformation.

These conceptual, reservoir-based descriptions of the water balance and groundwater dynamics allow for the assessment of large regions but are limited with respect to high spatial resolution. To account for more realistic and detailed subsurface water and nitrate transport, spatially-distributed hydrological models have been linked with models simulating carbon (C) and nitrogen turnover and anthropogenic land-use, e.g., Duretz et al. (2011) and Wlotzka et al. (2014). While the latter study discusses in-depth the use of a parallelized coupling strategy, the study by Duretz et al. (2011) focuses on N cycling in a mainly managed heterogeneous landscape including subsurface and atmospheric transport of N species.

In this study we present a detailed modeling approach that can aid in understanding short and long-term effects of different agricultural managements in order to assess their potential to mitigate nitrogen losses along aqueous and gaseous loss pathways. So far, similar studies that investigated nitrogen exports on the landscape scale with consideration of lateral water and nutrient transport followed simple balance-based approaches at large spatial scales suitable to, e.g., estimate N inputs to coastal waters (e.g., Arheimer et al., 2005). Here, we focus on small areas, e.g., field to catchment scale, which allows for the inclusion of microbial processes relevant for the production and consumption of NO_3^- and N_2O, like nitrification, denitrification (Kraus et al., 2015; Butterbach-Bahl et al., 2013), and spatially explicit lateral transport of water and dissolved nutrients at high levels of detail.

We couple the comprehensive process-based, biogeochemical model LandscapeDNDC (Haas et al., 2013; Grote et al., 2009) and the process-based, fully-distributed hydrological Catchment Modeling Framework (CMF) (Kraft et al., 2011), that allows considering C and N cycling, nutrient transport and their feedback within a catchment. Next, we investigate the pathways of nitrate transport and N based trace gas emissions and evaluate them in the context of pollution swapping. To demonstrate the potential of our approach we explore the effects of different widths of vegetated riparian buffer strips to reduce nitrogen loads into surface waters from farmland. The spatial extent of the investigated domain is one hectare that is discretized into cells of 5×5 meters. All models have a timestep size of one hour, hence data exchange between models occurs at that interval in order to update their boundary conditions.

This study builds upon work in Haas et al. (2013) who used a Python-based coupling approach demonstrating displacement processes of water and nutrients on a two-dimensional hillslope with fairly coarse resolutions both in time and space. They applied similar models, however, did not investigate in-depth buffer strip functioning nor assessed or discussed mitigation strategies.

2. Materials and methods

All simulations in this study are performed using the